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Research and Development Technical Report
ECOM-3259

VARIABILITY OF BALLISTIC WINDS
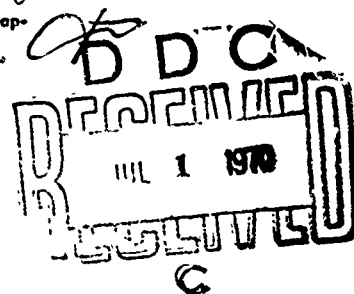
by

Marvin J. Lowenthal
Raymond Bellucci

April 1970

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DEPARTMENT OF THE ARMY
UNITED STATES ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERESEY

Correction to R&D Technical Report ECOM-3259

Variability of Ballistic Winds
by
Marvin J. Lowenthal and Raymond Bellucci
April 1970

CORRECTION - Page 7

The definitions of the correlation coefficients should be corrected to read:

R_{12} = correlation coefficient between Δv and V

R_{13} = partial correlation coefficient between Δv and H

R_{23} = partial correlation coefficient between V and H

NOTICES

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TECHNICAL REPORT ECOM-3259

VARIABILITY OF BALLISTIC WINDS

By

Marvin J. Lowenthal and Raymond Bellucci
Atmospheric Physics Technical Area
Atmospheric Sciences Laboratory

April 1970

DA Task No. 1T0-62111A-126-05-12

U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY

ABSTRACT

Temporal wind variability is examined from the standpoint of using wind speed as the independent variable since correlations of wind variabilities with height show no significant values.

Data from ballistic tests made at Ft Huachuca, Arizona, are analyzed to formulate equations for variabilities of zone and ballistic winds for time intervals of 2 to 8 hours. The equations involve not only the square root of the time (similar to earlier investigations), but also the mean wind speed.

Analysis of the Meppen, West Germany, data is added to extend the time lag to 1 hour and to confirm the validity of the formula for Western Europe.

Contents

FIGURES

TABLES

VARIABILITY OF BALLISTIC WINDS

INTRODUCTION

Over the past 20 years, more than 100 papers have been published on temporal wind variability. Time periods have ranged from seconds to days, and levels from the lowest boundary layer to the mesosphere have been investigated. A strong motivation is required to add to this already formidable documentation so that previous efforts are not duplicated nor earlier works merely confirmed.

If one examines the published reports, it is found that they generally follow a given procedure. Wind differences at various time lags are calculated for a given level, either at a constant pressure surface (700 millibars (mb), 500 mb, etc.) or a constant height (1000 meters, 3000 meters, etc.).

The dependence of temporal wind variability upon height is prevalent in almost all meteorological literature, starting with Durst's work in 1954[1] where σ, the root-mean-square variation of the wind with time, was given as a function of altitude. Others such as Arnold and Bellucci,[2] and Bellucci and Gabriel,[3] investigating the lowest 30,000 feet, showed a constant variability dependent only on the square root at the time. However, most investigators found that the variability increased from the lowest levels to about 30,000 feet, then decreased upwards. Due to the scarcity of data, variability estimates are less reliable above 80,000 feet, especially for time lags of less than 2 hours. A typical chart is shown in Fig. 1, representing a composite of data from several investigations (see references 4,5,6,7,8 & 9). The variability maximum at 30,000 feet is clearly shown for all time lags.

While all investigations point to a maximum of wind variability associated with the level of the maximum wind, there are no reports describing the relationship of wind variability to wind speed. Mr. A. G. Matthewman, in a Meteorological Working Paper (MWP/2) for NATO Army Armaments Group AC/252 (Panel XII), suggests a slightly different approach. His proposed variability formula for Western Europe is:

$$\sigma_t = 0.2\sigma \, t^{0.5} \qquad 1/2 \text{ hr} < t < 24 \text{ hrs} \qquad (1)$$

where σ is the climatological standard deviation (in knots) at a particular level.

The values of σ are interpolated from U. S. Navy charts[10] for given pressure levels, i.e., 850 mb, 700 mb, etc. Here a multiplicative factor is introduced to account for the nonconstancy of the variability with height. In essence, the factors are associated with fixed pressure levels above the surface, still using height as the independent variable. While the formula is an improvement over the earlier formula of Arnold and Bellucci (loc.cit.),

$$\sigma = 3.5 \, t^{0.5} \qquad 1 < t < 12 \text{ hrs,} \qquad (2)$$

the physical reasoning behind the use of altitude is absent.

DISCUSSION

It seems reasonable to investigate the variability problems by considering all the pertinent parameters, i.e., wind variation, wind speed, height, and time lag to determine for any time interval the parameter that correlates best with wind variation. Thus, an equation of the form

$$\Delta V = A + Bv + Ch \qquad (3)$$

where ΔV is the wind difference between any two observations, V is the mean wind, h is the height (A, B, C, are constant) was considered a more accurate equation for the time variability of winds.

For this study, the vector wind difference between two observations v_1 and v_2 was used as a measure of wind variability,

$$\Delta V = \vec{V}_2 - \vec{V}_1 \qquad (4)$$

For any given time-lag, the mean absolute values of all such pairs are computed to give the variability of the wind, w. Expressed mathematically,

$$W = \frac{1}{n} \sum |\Delta V| \qquad (5)$$

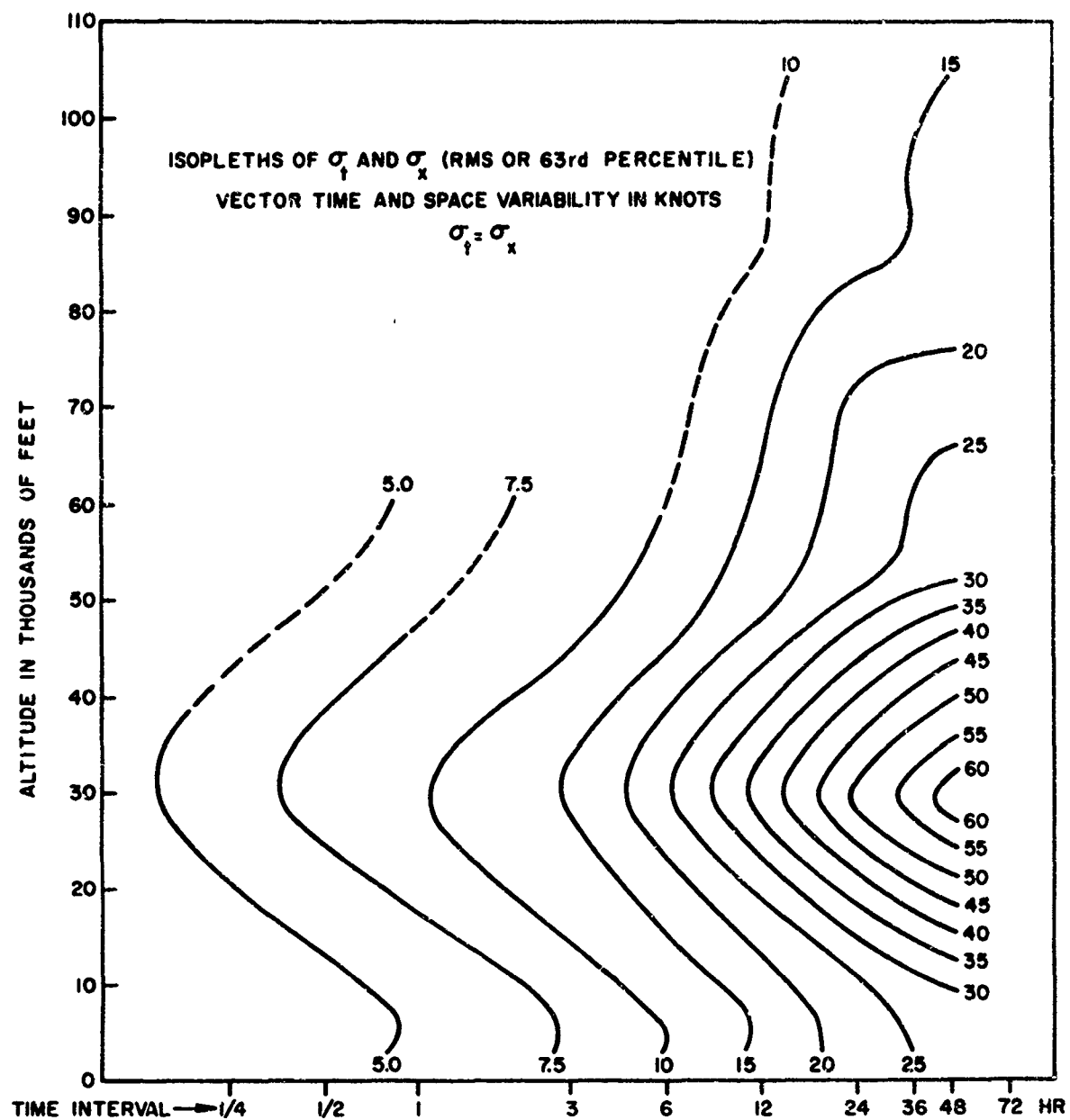where n is the number of observations.

2

Figure 1. Dependence of Observed Time Variability of Vector Winds
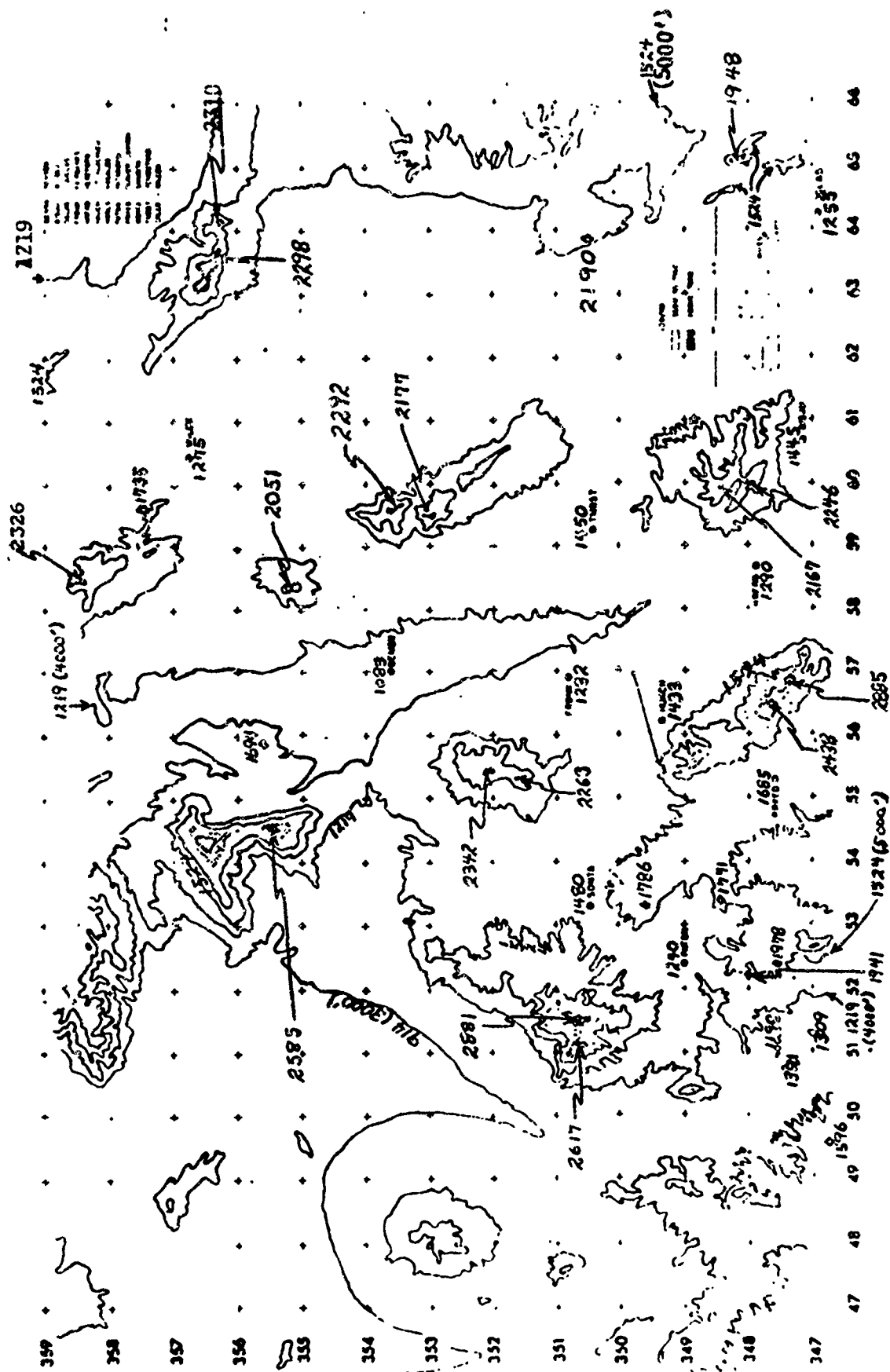
(AFTER ELLSAESSER (9))

3

Figure 2. Objective analysis grid showing observing stations. (Grid units are based on the 10,000-m Universal Transverse Mercator Grid (Zone 12), with the last four digits of the grid numbers omitted.)

4

While w, the statistic used, is somewhat smaller than the root-mean-square value of the wind variations used by many investigators, tests run on several samples of data show insignificant differences in the two results.

A question now arises: What wind speed should be associated with a given ΔV, since a pair of observations taken several hours apart is involved. Duplicate calculations were made using 1) ΔV_1, the earlier wind speed, and 2) the arithmetic mean of the two wind speeds, $1/2(V_1 + V_2)$. Variability results were almost identical for both sets of computations.

Data for the investigation were taken from the Artillery Meteorological Study,[11] a field study made in the Fort Huachuca, Arizona, area during January and February 1965. A meso network of 12 rawin stations was established to obtain synoptic soundings in conjunction with the firing of two 8-inch howitzers. Simultaneous balloon flights were made at 2-hour intervals from 0600 LST to 1400 LST on 16 test days, a total of 960 soundings. Data were reduced by computer after careful editing to remove reading and punching errors and gross errors in the angular recorder print-out.[12]   The stations and their locations are shown in Fig. 2.

Since the field tests were intended for artillery purposes, winds were computed for the artillery zones, as shown below in Fig. 3. The mean wind for the layer was determined and that value attributed to the mid-point of the zone, i.e., for Zone 1 the wind is assigned to 350 meters. Similarly, computations were performed using standard artillery weighting factors[13] in order to determine the variability of ballistic winds.

Zone limits (meters)	Zone No.	Midpoint height (meters)	Density (gms/m³)	Temperature	
				°C.	°K.
Surface	00	0	1,225.0	15.0	288.2
0 200	01	100	1,213.3	14.4	287.5
200 500	02	350	1,181.4	12.7	285.9
500 1,000	03	750	1,139.2	10.1	283.3
1,000-1,500	04	1,250	1,084.6	6.9	280.0
1,500-2,000	05	1,750	1,032.0	3.6	276.8
2,000-3,000	06	2,500	957.0	−1.2	271.2
3,000-4,000	07	3,500	860.4	−7.7	265.5
4,000-5,000	08	4,500	777.0	−14.2	259.0
5,000-6,000	09	5,500	697.4	−20.7	252.5
6,000-8,000	10	7,000	590.0	−30.5	242.7
8,000-10,000	11	9,000	467.0	−43.4	229.8
10,000-12,000	12	11,000	364.8	−56.4	216.8
12,000-14,000	13	13,000	266.6	−56.5	216.7
14,000-16,000	14	15,000	194.8	−56.5	216.7
16,000-18,000	15	17,000	142.3	−56.5	216.7

Figure 3. Artillery Zone Structure.

5

Results

Returning to the general variability equation given earlier, Eq. (3), $\Delta V = A + BV + Ch$, coefficients A, B, and C are determined by standard linear regression techniques,[17] and their relative size indicates the degree of dependence of ΔV on V or H. Table 1 presents the values of the coefficients for the indicated time lags, along with the number of pairs used in the computations.

TABLE 1

Regression Coefficients: Unweighted Zone Winds

$$\Delta V = A + BV + CH$$

t (hours)	n	A (knots)	B (knots)	C (knots)
2	8586	3.75	0.12	-0.00015
4	6303	5.49	0.16	-0.00022
6	4160	6.74	0.22	-0.00030
8	2019	7.67	0.27	-0.00043

It is obvious that the coefficients vary with time lag, and furthermore, the variation is not linear. To determine the functional relationship, plots of Δv against the coefficients were constructed on log-log paper. The resultant slope indicated that the exponent of "t" should be 0.5. The equations for each time lag are shown below:

Variability of Zone Winds

$\Delta t = 2$ hrs	$\Delta v = (2.65 + 0.08V - 0.0001\ H)t^{0.5}$
$\Delta t = 4$ hrs	$\Delta v = (2.75 + 0.08V - 0.0001\ H)t^{0.5}$
$\Delta t = 6$ hrs	$\Delta v = (2.75 + 0.09V - 0.0001\ H)t^{0.5}$
$\Delta t = 8$ hrs	$\Delta v = (2.72 + 0.09V - 0.0002\ H)t^{0.5}$

6

Combining these equations into a single equation we obtain:

$$\Delta V = (2.7 + 0.08V - 0.0001 H)t^{0.5} \qquad 2 < t < 8 \text{ hr} \qquad (6)$$

Equation (6) makes it very clear that there is virtually no dependence of wind variation with height. This is emphasized when the correlation coefficients are examined as indicated in Table II.

TABLE II

Partial Correlation Coefficients (Zone Winds)

t (hours)	R_{12}	R_{13}	R_{23}
2	0.42	0.08	0.44
4	0.46	0.09	0.45
6	0.50	0.09	0.45
8	0.56	0.08	0.46

R_{12} = correlation coefficient between Δv and H

R_{13} = partial correlation coefficient between Δv and H

R_{23} = partial correlation coefficient between Δv and H

Note that the wind variability correlates well with the wind speed ($R \approx 0.5$), but not at all with height ($R < 0.1$), while the wind speed itself correlates with the height. It is this last correlation that causes an apparent relationship of wind variability with height, which is noted so often in the literature.

Ballistic Winds

When the zone winds are weighted with the standard weighting factors [12] to give an integrated wind, a smoothing results which should tend to reduce the wind variability. This is indeed the case as noted below.

7

Variability of Ballistic Winds

$\Delta t = 2 \text{ hrs} \quad \Delta V_B = (2.49 + 0.07V_B - 0.00016 \ H)t^{0.5}$

$\Delta t = 4 \text{ hrs} \quad \Delta V_B = (2.35 + 0.08V_B - 0.00014 \ H)t^{0.5}$

$\Delta t = 6 \text{ hrs} \quad \Delta V_B = (2.38 + 0.09V_B - 0.00013 \ H)t^{0.5}$

$\Delta t = 8 \text{ hrs} \quad \Delta V_B = (2.36 + 0.09V_B - 0.00013 \ H)t^{0.5}$

where ΔV_B is the variability of ballistic winds, and V_B is the ballistic wind speed.

Again, combining to form a single equation:

$$\Delta V_B = (2.4 + 0.08V_B - 0.0001 \ H)t^{0.5} \quad 2 < t < 8 \text{ hrs} \qquad (7)$$

Note that V from Eq.(6) and V_B from Eq.(7) are different. In general, the ballistic wind is about 80% of the unweighted wind for the comparable zone. In this study the mean values of the zone and ballistic winds were 26.5 knots and 21 knots respectively, conforming well to the ratio established from other studies.

The correlation coefficients are not significantly different from those of Table II, as noted from Table III below:

TABLE III

First-Order Correlation Coefficients (Ballistic Winds)

t (hours)	R_{12}	R_{13}	R_{23}
2	0.34	0.08	0.49
4	0.46	0.02	0.49
6	0.53	0.06	0.49
8	0.57	0.08	0.49

The almost total lack of correlation between wind variability and height would lend credence to the dropping of the "H-term" in

the variability equations. In the case of application to artillery where all maximum ordinates are less than 20 km and most below 10 km, there is additional justification. The simplified variability equations become;

$$\Delta V = (2.7 + 0.08V)t^{0.5} \qquad 2 < t < 8 \text{ hrs} \qquad (8a)$$

$$\Delta V_B = (2.4 + 0.08V_B)t^{0.5} \qquad 2 < t < 8 \text{ hrs} \qquad (8b)$$

It will be noted that the older Eq. (2) on wind variability, which was an average value of many observations, may be considered as the wind variability associated with a 10-knot wind, which is a good estimate of the mean wind observed during the investigation.

Since meteorological data from the Fort Huachuca tests covered a period of 2 to 8 hours, extension of the period of validity of Eqs. (8a) and (8b) from such data is not possible. Some references, however, can be made from general considerations. It is obvious that Eqs. (8a) and (8b) cannot be used for long time intervals, since the wind variability would take on impossibly large values. A different form of variability equation must be employed that follows from the standard vector deviation of the difference of two vectors:

$$\sigma_{1-2} = (\sigma_1^2 + \sigma_2^2 + \sigma_1\sigma_2 r_{1,2})^{0.5} \qquad (9)$$

where σ_1, σ_2 are standard deviations of two vectors, and $r_{1,2}$ is the correlation coefficient.

In the case of wind variability with time:

$$\sigma_{1-2} = \sigma$$

$$\sigma_1 = \sigma_2 = \sigma$$

$$\sigma_t = \sqrt{2(1-r_t)}\ \sigma \qquad (10)$$

For very long time periods, $r \to 0$, hence:

$$\sigma_t = \sqrt{2}\ \sigma \qquad (11)$$

9

Thus the variability approaches $\sqrt{2}$ times the standard deviation of the wind as a limit.

The Meppen trials[14] use radiosonde data with longer time separations between flights - up to 24 hours. An analysis of those data are contained in the Addendum to this report.

At the other end, investigations of R. Bellucci[15] have shown that for very short time intervals (less than one hour) wind variabilities do not follow the "square root" law. Thus, Eqs. (8) should not be used for t <1. Since Eq. (2) of Arnold and Bellucci indicates a lower limit of 1 hour, the lower limit of our Eqs. (8) is tentatively set at 1 hour pending verification from Meppen Analysis.

The equations now become:

$$\Delta V = (2.7 + 0.08V)t^{0.5} \quad 1 < t < 8 \text{ hrs} \tag{12a}$$

$$\Delta V_B = (2.4 + 0.08V_B)t^{0.5} \quad 1 < t < 8 \text{ hrs} \tag{12b}$$

CONCLUSIONS

In this report, a new equation for wind variability has been derived for periods between 1 hour and 8 hours, which depends not only on the time interval between observations, but also on the wind speed itself. It would be desirable to have a complete formulation for all periods, but as noted, the time lag becomes less important at short as well as at very long periods.

Equation (10) should be made applicable for all periods, but the difficulty in determining the correlation coefficient makes it somewhat unwieldly. An assumption is generally made that the correlation coefficient is exponential, viz.:

$$r_t = e^{-\alpha t} \tag{13}$$

This is probably an oversimplification since investigations [1,9,16] show that r varies with geography, season, altitude, time lag, etc. In addition, for time lags larger than 36 hours, there is a systematic departure of "r" from Eq.(13). A re-examination might be indicated using wind speed as the independent variable.

Variability studies for short time lags are difficult because of the requirement for multiple ground equipments and the inherent measurement errors that effectively mask the small variability associated with

periods of a few minutes. A study of wind variability in the 2- to 10-minute range conducted by R. Bellucci (op.cit.) using pibal balloons, showed that wind variabilities were approximately 25% of the wind speed and essentially independent of time in the 2- to 10-minute range.

The relative unimportance of time in short-period wind variability may be noted from examination of the work of Plagge and Smith (op.cit.). The values of the time variability of wind for one-quarter hour and one-half hour are not significantly different, and definitely do not vary as the square root of time lags.

Thus, a complete explicit formulation of wind variability in terms of wind speed and time lag would be complex, involving at least three terms. The first term would apply to short time periods, another to very long periods, and the third term would be similar to our Eqs. (8). Beyond its period of validity, the value of each term would be almost negligible compared to the applicable terms, hence its contribution is felt only when required.

Symbolically

$$\Delta W = S + M + L \tag{14}$$

where the value of $S \to 0$ when $t > 1$ hour,

and the value of $M \to 0$ when $t < 1$ hour or $t > 8$ hours,

and the value of $L \to 0$ when $t < 8$ hours.

The limits of "t" are meant to be illustrative rather than definitive. Considerably more data, especially at the shorter time intervals, are required before any reliable relationships can be established.

11

ADDENDUM

Analysis of Meppen Data

The Meppen data from the Summerwind Program were analyzed following the procedures outlined earlier in the report, to the extent that the data would allow. In that program, nine upper air stations were established with soundings made at intervals as short as 1 hour. While the instrumentation for measuring the winds was, in most cases, different from that employed at Fort Huachuca, the care with which the data were taken makes the inclusion of this work worthwhile.

Results

The regression coefficients for ballistic winds, with the number of paired values, are shown in Table IV. It will be noted that the number of cases is far less than in the Fort Huachuca Study, and that there is a sharp decrease between 6 and 8 hours. The number of data pairs remains small until the 24-hour interval, with the attendant loss in significance of the results between 8 and 15 hours.

TABLE IV

Ballistic Winds (Upper)

Regression Coefficents

$$\Delta V = A + BV + CH$$

t (hours)	n	A (knots)	B	C
1	2135	2.45	0.085	0.00013
2	1422	3.11	0.081	0.00028
3	2077	3.16	0.132	0.00021
4	1925	4.13	0.119	0.00018
6	1314	3.75	0.200	0.00040
8	160	3.21	0.159	0.00031
10	417	3.05	0.294	0.00001
12	255	1.22	0.455	-0.00017
15	228	0.68	0.459	0.00010
24	1357	-1.14	0.471	-0.00015

Proceeding as before, we form equations for each time lag by dividing out $t^{0.5}$ The results are shown on the following page:

Variability of Ballistic Winds

$t = 1 \text{ hr}$ $\Delta V_B = (2.45 + 0.09\ V_B + 0.00013\ H)t^{0.5}$

$t = 2 \text{ hrs}$ $\Delta V_B = (2.20 + 0.06\ V_B + 0.00019\ H)t^{0.5}$

$t = 3 \text{ hrs}$ $\Delta V_B = (1.83 + 0.08\ V_B + 0.00012\ H)t^{0.5}$

$t = 4 \text{ hrs}$ $\Delta V_B = (2.06 + 0.06\ V_B + 0.00010\ H)t^{0.5}$

$t = 6 \text{ hrs}$ $\Delta V_B = (1.53 + 0.08\ V_B + 0.00002\ H)t^{0.5}$

$t = 8 \text{ hrs}$ $\Delta V_B = (1.14 + 0.06\ V_B + 0.00011\ H)t^{0.5}$

$t = 10 \text{ hrs}$ $\Delta V_B = (0.97 + 0.09\ V_B + 0.00003\ H)t^{0.5}$

$t = 12 \text{ hrs}$ $\Delta V_B = (0.35 + 0.13\ V_B - 0.00005\ H)t^{0.5}$

$t = 15 \text{ hrs}$ $\Delta V_B = (0.17 + 0.12\ V_B + 0.00025\ H)t^{0.5}$

$t = 24 \text{ hrs}$ $\Delta V_B = (-0.2 + 0.10\ V_B - 0.00003\ H)t^{0.5}$

     Comparison of the above results and those given earlier shows excellent agreement up to 6 hours and only fair agreeement at 8 hours. For long periods, Eq.(7) is obviously invalid. The discrepancy at 8 hours is strange since a similar time lag at Fort Huachuca gives results as predicted. However, there is one order of magnitude difference in the number of cases. It may well be that 160 cases are not a representative sample for the statistic.

Weighting the various time lags to form one equation, we obtain:

$$\Delta V_B = (2.0 + 0.07\ V_B + 0.0001\ H)t^{0.5} \qquad 1 < t < 8 \text{ hr} \qquad (15)$$

Finally, simplifying by ignoring the height term,

$$\Delta V_B = (2.0 + 0.07\ V_B)t^{0.5} \qquad 1 < t < 8 \text{ hrs} \qquad (16)$$

     As postulated earlier, we have confirmed that the Eqs. (8) are valid for 1 hour. The upper limit, 8 hours, is still within acceptable confidence limits, the standard error of estimate being 4.7 knots.

13

The concept that wind variability for longer periods does not follow the "$t^{0.5}$" law is very evident from the Meppen data since there is scarcely any difference in the 12- and 24-hour wind variabilities. If additional data were available, the variabilities would continue to increase very slowly since the limiting value, $\sigma\sqrt{2}$, has not yet been reached.

The value of the constant "Λ" $\sim|0.2|$ for the two longest time lags (15- and 24-hours) is insignificant compared to the "BV" term. It is noteworthy also that the coefficient of V is relatively invariant, approximately one-tenth of the mean wind speed. This contrasts strongly with the variability for very short periods ($\sim$ few minutes), where the dependence is of the order of one-fourth or one-fifth the wind speed.

SUMMARY

The Meppen data confirms the validity of the proposed wind variability formula for the period of 2 to 8 hours, and extends the lower limit to 1 hour. The data likewise show that the formula cannot be used for time lags greater than 12 hours.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Winds						
Ballistic winds - variability						
Temporal wind						
Meppen-data analysis						